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REVE — a new industrial technology for biomass torrefaction: pilot studies

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ABSTRACT

Torrefaction is a well-known biomass pretreatment. However, some technical challenges still remain in terms of industrial development. With its origins in the food industry, the REVE technology is a very interesting potential solution which can meet some of these challenges such as achieving uniform treatment using the plug flow characteristics of the machine, the possibility of treating a wider range of input materials using vibrational transport techniques and benefiting from Revtech's process upscaling expertise. Using the same pilot unit, four types of biomass (wood chips, olive pips, pine barks and straw) have been torrefied at different temperatures (240 °C to 300 °C) for up to 30 min. A large range of torrefied products, including biochar, have been produced and analyzed (elemental analysis, heating values and grindability), validating the flexibility of REVE technology. Preliminary continuous runs with wood chips at 40 and 80 kg/h up 310 °C for 10 min have also been performed. With this pilot unit, wood chips can be continuously torrefied at 300 °C and 40 kg/h. Techno-economic aspects are finally discussed with a focus on energy consumption.

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1. Introduction

Considering its availability and cost, combined with increasing global energy demand and the depletion of fossil fuel, biomass is generally admitted as a being an important potential source of advanced fuels. The carbon neutral combustion of such fuels makes them sustainable and environmentally friendly. Furthermore, biomass is the only renewable source of sustainable carbon [1,2]. Several thermochemical conversion processes have been studied, such as fast pyrolysis and direct liquefaction to produce bio-oils [3], or gasification to produce combustible gas and syngas [4] which seems to be the most promising process [2].

However, the diversity of biomass physical and chemical compositions, which depends on its origin, makes its use complicated. Pretreatment appears necessary and torrefaction is considered as an effective method to increase the uniformity of feedstock [5]. Torrefaction is a biomass pretreatment at temperature ranging 200–300 °C for 10 min to 2 h, in the absence, or with low concentration, of oxygen [6]. Typically, a solid mass yield of 70% is reached from woody biomass, containing 90% of the initial energy content [1]. Best operating conditions depend on biomass, application, and the desired property enhancement: energy density, grindability, pelletability, water content, carbon content, higher heating value (HHV) [4]. Note that torrefaction degree is lower for pelletability [7] than for coal-like grindability [1] or carbon content for soil amendments [8].

In order to evaluate the degree of torrefaction, in addition to mass balances, physical and chemical properties have to be measured, calculated or evaluated. Product coloration can be a first indicator of a high degree of torrefaction, validated by proximate and ultimate analysis [9,10]. From ultimate analysis, van Krevelen diagrams can be plotted in order to compare torrefied products to lignite, bituminous or anthracite products [11,12]. Higher heating value (HHV), measured [10,13] or estimated from ultimate analysis [14], is a good indicator for energy yields and densification. Grindability is more difficult to estimate. Other than for its power consumption approach [1], the use of the coal Hargrove Grindability Index [15] or derivatives [16,17] is not obvious for torrefied biomass. Comparison of size distribution after milling is an easy first approach to evaluate the grindability improvement by torrefaction [16,18–20].

Interest of torrefaction for gasification [21–23], biomass to liquid (BtL) routes [24] or co-firing with coal [25] is clear but continuous industrial torrefaction plants with high flow rates are still rare. Technical challenges such as gas handling, process upscaling, product uniformity, flexibility in using different input material or heat integration have to be met. Most of the technologies use gases as a heat carrying medium which entails a high amount of gas to be treated and only few technologies can handle a large spectrum of particle sizes. Moreover, the principal technologies used such as screw reactors, drum reactors or belt conveyors have a limited scalability, making multiple production lines necessary [26].

Since its creation 15 years ago, REVTECH has developed and supplied the Vibrating Electrical Elevator and Reactor (REVE) throughout the world. These industrial machines have been successfully installed

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for roasting various food ingredients such as peanuts, barley or soya with flow rates up to 5 ton/h. This paper presents the validation of this robust, simple and modern technology, originating in the food industry, with high capacity perspectives for biomass torrefaction. Four types of biomass (wood chips, pine barks, olive pips and straw) are studied under several operating conditions in a 100 kg/h pilot unit. Mass yields are calculated and analyses are performed in order to evaluate degree of torrefaction reached using this new technology.

2. Materials and methods

2.1. Materials

The four raw materials used in this study are not pretreated or sieved, and are torrefied as received (wet basis). Wood chips (oak), from a local wine company, are stored in big bags, with chip sizes ranging 5 to 20 mm. Pine bark, generally used as mulch, is stored in hermetic bags, with particle sizes ranging 10 to 40 mm. Olive pips are directly recovered after processing from a local olive mill and stored in big bags, with a diameter of 5 mm. Straw, generally used as rabbit litter, is stored in air-tight bags, with fiber lengths ranging 20 to 100 mm.

Table 1 gives the moisture and bulk density (ρ_b) measured for all biomass types as well as ultimate analysis on dry basis. Ash content is not measured but average values are taken from Ref. [27] in order to not over-evaluate the oxygen content, calculated by difference. Higher heating values (HHV) are then calculated according to a correlation based on ultimate analysis [14].

2.2. Technology and pilot unit

The Vibrating Electrical Elevator and Reactor (REVE), which is a proven technology in the food industry, is based on three simple principles:

(1) The product is transported and mixed in a stainless steel spiral tube using vibrations induced by two off-balanced shaker motors. An off-balance shaker motor is a rotating motor equipped with eccentric weights. As these masses rotate they generate vibrations along a plane at right angles to the motor axis, whose frequency is determined by the speed of rotation and whose amplitude is proportional to the mass of the off-balance weights. To modify the residence time of the particles inside the spiral, three parameters can be changed: angle of attack of the motor, the position of the eccentric weights and the frequency of rotation of the motors.

(2) This stainless steel spiral tube is connected to a power transformer and heated by electricity flowing in the wall of the tube using the principle of impedance tube heating. The product is heated by the contact with the hot tube. The tube therefore behaves as a hydraulic conduit for the product, an electrical resistance and a heat exchanger. An impedance tube heating system is a constant power system, which means that each meter of tube produces the same amount of power. Tube temperatures are measured by thermocouples type K which are connected to a PID power controller.

(3) During transportation in the confined spiral tube, the atmosphere is controlled with a possibility of inerting the process at low cost. At each turn of the spiral, gas/steam/air can be injected on one side of the reactor and be extracted on the other side of the reactor. In the case of biomass torrefaction, absence or low concentration of oxygen is required [6]. Therefore all the injection pipes are closed and vapors/gases are extracted which entails a low negative pressure inside the REVE. In this way, the reactor is maintained in an inert state.

Experimental studies are carried out using a pilot unit (Fig. 1) of the REVTECH Research and Development Department, with the following characteristics:

(1) A spiral tube with an external diameter of 88.9 mm (DN80) and a total length of 33.3 m on 8 turns.
(2) Vapors and gases can be extracted at all turns of the spiral tube. Extraction pipes are connected to a manifold with a negative pressure of −100 Pa.
(3) A solids recirculation system is used in order to increase residence times and sample easily.

2.3. Methods

A residence time of 30 min seems to be the upper limit to keep the torrefaction process economically feasible [1]. This is the reason why longer residence times are not studied in this work.

Table 2 gives operating conditions of torrefaction runs with the recirculation system, needed to increase the residence time with this pilot unit. The stainless steel tube is heated up and monitored using thermocouples. Once the REVE is at the desired temperature, motors are started and vibrations begin. The reactor is fed constantly until the first particles appear at the exit. Mass of biomass introduced (m_B) and single loop time (τ) are measured and equivalent mass flow rate (Q_{eq}) is calculated. The recirculation system is put into place in order to reach the final residence time (t) by making several loops. Samples of each loop can be taken using the recirculation system. During the run, all gases and volatiles are extracted to prevent condensation inside the tube, and flow through filters before being evacuated to the outside. At the end of the run, corresponding to the end of a whole number of loops, solids are continuously recovered and cooled down using ambient air.

Biomass density and particle size explain the differences in mass flow rate from one biomass to another. Moreover, the differences in final residence times (t) are linked to the single loop times (τ) which depend on the type of biomass.

Preliminary additional studies are conducted on the same pilot unit with wood chips to show the potential use of the pilot unit as a continuous demonstration plant (Table 3). For these runs, motor angles have been changed in order to increase the time of a single loop to 10 min ($t = \tau$), allowing continuous operation (without the recirculation system). As a consequence, mass flow rate is decreased to keep a similar filling ratio, A_F, which was 10% for initial runs with wood chips. The impact of tube temperature (T) and mass flow rate (Q) are studied and discussed in Section 3.6.

2.4. Analysis of solids

Initial moisture of biomass is determined by mass loss after 24 h in a muffle furnace (Thermolyne F6000 Furnace) at 105 °C. Initial biomass bulk density is determined by weighing 1 liter of biomass.

Ultimate analysis is made on dried products using a Thermo Flash EA 1112 to measure carbon (C), hydrogen (H) and nitrogen (N) content. Ash content is not measured but average values are taken from Ref.

Table 1
Moisture (wt.%), bulk density (g/cm^3), ultimate analysis (wt.% on dry basis), and HHV (on dry basis) of raw biomass types.

Biomass	Moisture	ρ_b	C	H	N	Ash [a]	O [b]	HHV [c]
Wood chips	11.8	0.28	48.06	5.95	0.10	1.0	44.9	19.12
Olive pips	20.3	0.66	51.27	6.73	1.23	2.0	38.8	21.76
Pine barks	59.7	0.33	51.02	5.25	0.36	2.5	40.9	19.71
Straw	11.0	0.05	43.05	5.82	0.84	5.0	45.3	17.08

[a] Average value from Ref. [27].
[b] Calculated by difference.
[c] Higher heating value in MJ/kg according to Ref. [14].

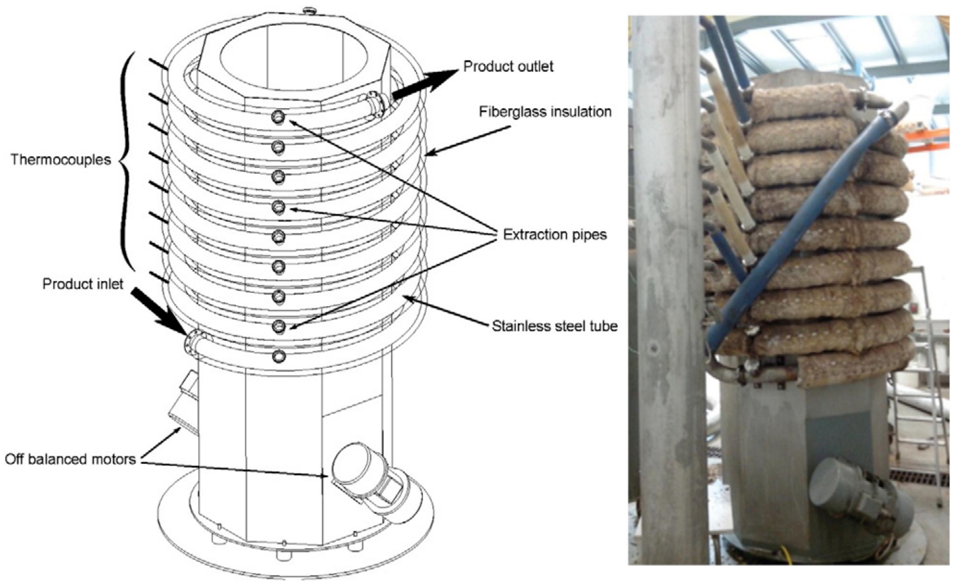

Fig. 1. Pilot unit of REVE technology for biomass torrefaction.

[27] for raw biomass. After torrefaction, it is assumed that ashes are concentrated in solids [28,29]. This is done in order to not too over-evaluate the oxygen content, calculated by difference.

Grindability is evaluated by comparison of particle size distribution after grinding. The blade grinder used is provided by MCR equipment and sieves (100 μm, 250 μm, 500 μm, 710 μm, 1 mm and 2 mm) are provided by Retsch. For each product, 4 g of solids is ground for 20 s and then sieved. Each particle size group is weighed using a scale with a precision of 0.001 g (KERN PFB 120-3).

3. Results and discussion

3.1. Outcome of new technology

All biomass types were easily torrefied, up to biochar, including wood chips, pine bark and olive pips. Due to the plug flow properties of the REVE [30], treatment and outlet products show a high uniformity. The confined spiral tube, coupled with extraction pipes, self-inert the reactor and prevent tar condensation inside the tube. As a consequence, an inert (nitrogen) flow is not necessary to inert the reactor and gas and volatiles which are extracted are not diluted, increasing the gas heating value.

Whatever the initial moisture, all biomass types have been treated as received. It means that heating, drying and torrefaction steps occurred in the REVE. Degree of torrefaction is well controlled by both tube temperature and residence time for given biomass, mass flow rate and tube diameter. Product characterizations and analysis, as well as mass and energy yields, are discussed in subsequent sections and confirm this.

3.2. Product coloration

Coloration of outlet product is a great initial indicator of torrefaction degree. Fig. 2 represents the color evolution of wood chips, olives pips, straw and pine barks at several degree of torrefaction. For each biomass, it can be clearly seen from the top left corner to the bottom right corner the influence of both temperature and residence time, which could be combined into a severity factor [31]. From wood chips, olive pips and pine barks, dark solids are obtained under the most severe conditions.

In the case of wood chips, there is clearly a non-color change period of about 5 min which corresponds to the heating and drying step. At the end of this period, torrefaction (dark coloration) is progressive but quicker with the increase of temperature. The color of the wood chips after 30 min of torrefaction at 260, 280 and 300 °C are similar to those from Ref. [9].

Olive pips were taken directly after milling and are slightly wet. The loss of humidity during the heating and drying steps make them appear lighter and cleaner than the raw material. The long non-color change period for olive pips, more than 18 min at 260 °C, can be explained by the higher initial moisture but mainly by a high heat capacity impacting the heating step. Once olive pips are at torrefaction temperature, the dark coloration is very quick and seems to be stable with the increase of residence time.

The high initial moisture of pine bark (59.7%) mainly explains the long drying step, around 10–12 min at 260 °C and 280 °C. After this period the dark coloration is progressive for both temperatures.

In the case of straw, the drying and heating steps are very short because of its low initial moisture and the high surface area to volume ratio. This is also the reason why 240 °C was considered sufficient in this study in order to prevent product degradation which happens even at 260 °C.

3.3. Elemental composition of torrefied biomass

Table 4 gives results from ultimate analysis of all torrefied biomass types. For every biomass, impact of temperature and residence time

Table 2
Operating conditions of torrefaction runs with recirculation system.

Biomass	m_B (kg)	τ (min)	Q_{eq} (kg/h)	T (°C)	t (min)
Wood chips	5.3	3.75	85	260-280-300	3.75 to 30
Pine barks	6	4	95	260-280	4 to 32
Olive pips	14	6	140	260-280	6 to 30
Straw	0.5	3.25	10	240	3.25 to 29.25

Table 3
Operating conditions of wood chips torrefaction continuous runs.

T (°C)	t (min)	Q (kg/h)	A_F (%)
280	10	40	13
300	10	40	13
300	10	80	26
310	10	80	26

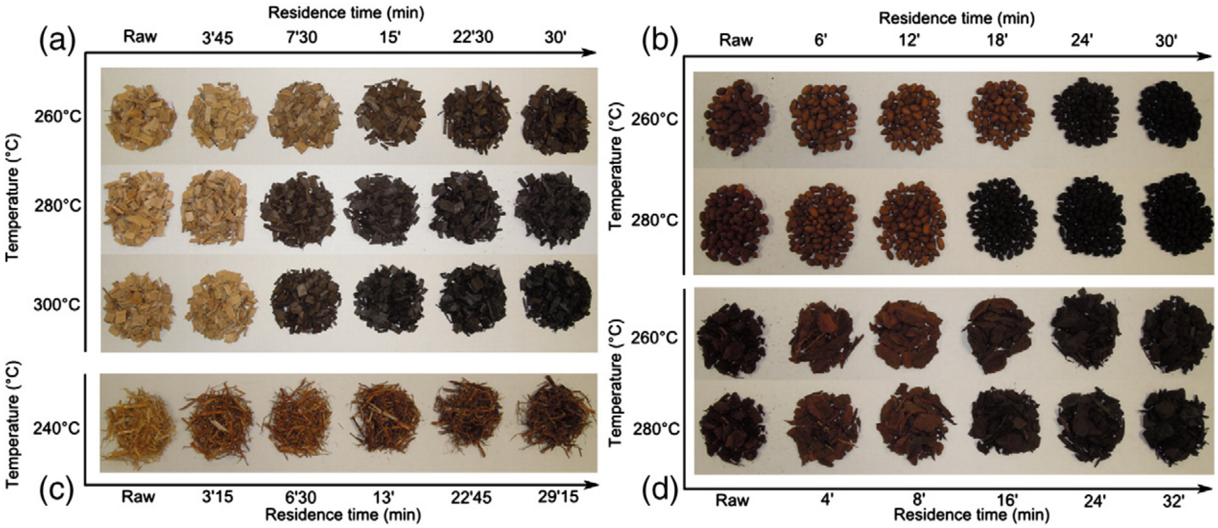

Fig. 2. Impact of temperature and residence time on coloration of torrefied (a) wood chips, (b) olive pips, (c) straw and (d) pine barks.

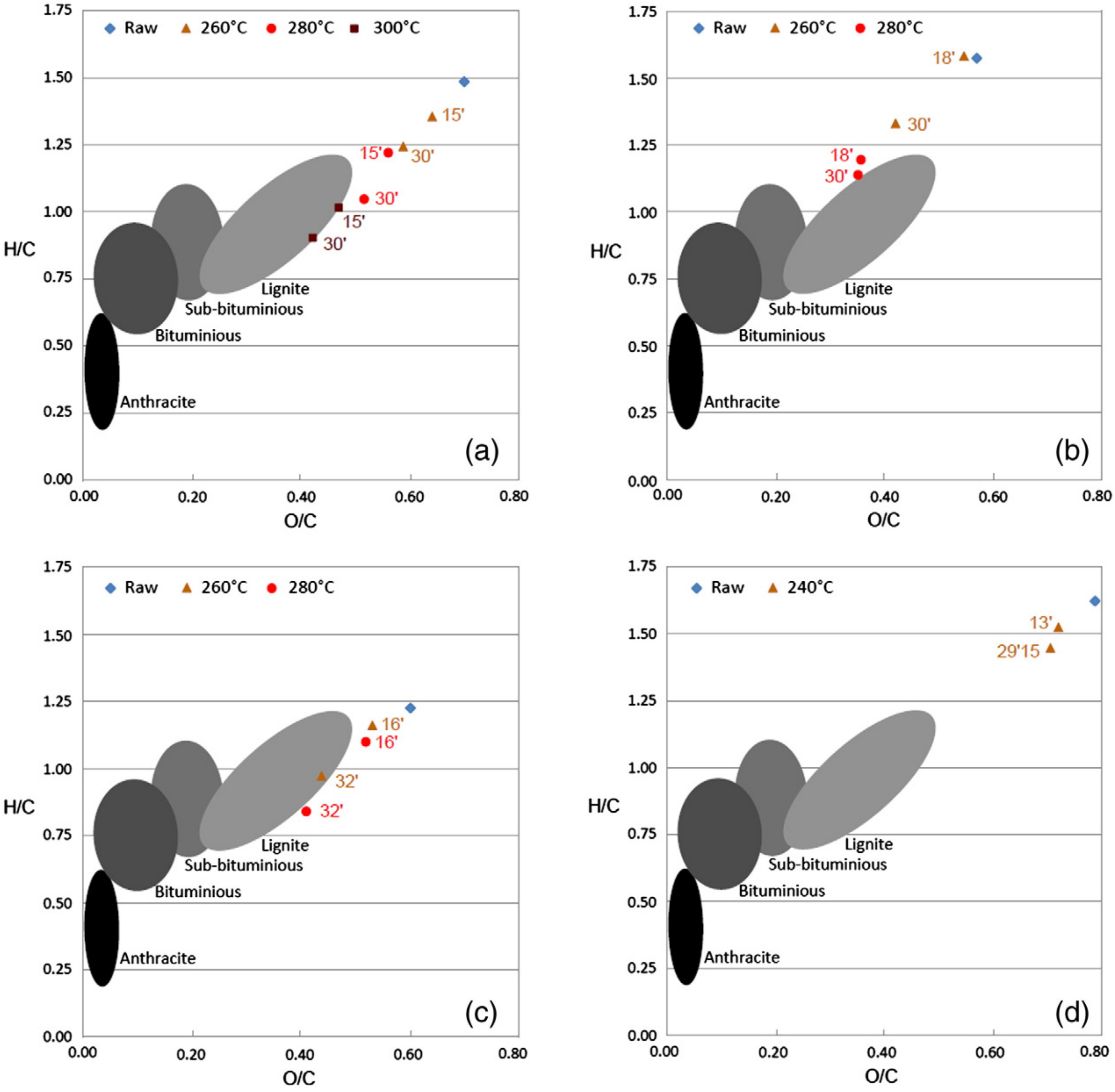

Fig. 3. Impact of temperature and residence time on elemental composition (van Krevelen diagram) of torrefied (a) wood chips, (b) olive pips, (c) pine barks and (d) straw.

on elemental composition can be appreciated. Moreover, higher heating values (HHV) can be estimated from ultimate analysis using the following Dulong-like correlation, with atom contents in percent and HHV in MJ/kg [14]:

$$HHV = 0.3491\ C + 1.1783\ H + 0.1005\ S - 0.1034\ O - 0.0151\ N - 0.0211\ Ash$$

In all cases, there is an increase of C content and HHV with the increase of both temperature and residence time. Under the most severe conditions, there is a HHV increase of 19% for wood chips, 17% for olive pips, 13% for pine barks and only 5% for straw. Elemental compositions and HHV agree with literature for similar biomass and torrefaction conditions [12].

Recalculated on a dry and ash free basis, elemental composition can be plotted on a van Krevelen diagram, representing H/C ratio according to O/C ratio. Fig. 3 compares torrefied biomass composition to different kinds of coal composition, based on Ref. [12]. From wood chips, olive pips and pine bark, under the most severe conditions, torrefied products show compositions close to lignite and can be assimilated to biochars.

These diagrams are also useful to evaluate the degree of torrefaction and confirm observations based product coloration. First of all, the slope of the composition trend line is generally observed [11,29] and mainly corresponds to a dehydration phenomenon [12]. In the case of wood chips, the progressive evolution of torrefaction degree appears clearly with the control of both temperature and residence time. The long drying and heating steps for olive pips are also confirmed, with the composition of the solid at 260 °C for 18 min being similar to the raw olive pips. Moreover, the similar composition of olive pips at 280 °C for 18 and 30 min also confirms the quick torrefaction and stabilization once the drying and heating steps have been achieved. Final composition seems to mainly depend on torrefaction temperature. Observations made with the progressive torrefaction degree of pine bark and the low torrefaction degree of straw are also confirmed by van Krevelen diagrams.

Table 4
Ultimate analysis (wt.% on dry basis), and HHV (on dry basis) of torrefied biomass.

Biomass	T (°C)	t (min)	C	H	N	Ash [a]	O [b]	HHV [c]
Wood chips	260	15	50.23	5.67	0.11	1.0	43.0	19.74
		30	52.16	5.40	0.12	1.4	40.9	20.31
	280	15	53.20	5.41	0.14	1.4	39.8	20.80
		30	55.42	4.84	0.13	1.4	38.2	21.07
	300	15	57.53	4.87	0.13	1.4	36.0	22.06
		30	60.09	4.52	0.13	1.4	33.8	22.78
Olive pips	260	18	52.03	6.85	1.35	2.0	37.8	22.27
		30	57.57	6.37	1.19	2.9	32.0	24.22
	280	18	61.09	6.09	1.21	2.9	28.8	25.45
		30	61.55	5.84	1.13	2.9	28.6	25.33
Pine barks	260	16	53.83	5.22	0.31	2.5	38.1	20.95
		32	57.70	4.69	0.30	3.6	33.7	22.10
	280	16	54.45	5.01	0.31	2.5	37.7	20.95
		32	59.37	4.18	0.38	3.6	32.5	22.22
Straw	240	13	45.11	5.71	0.75	5.0	43.4	17.87
		29,25	45.67	5.49	0.74	5.0	43.1	17.84

[a] Average value from Ref. [27] and concentrated for dark solids.
[b] Calculated by difference.
[c] Higher heating value in MJ/kg according to Ref. [14].

3.4. Biomass grindability

Using a blade grinder, the grindability improvement has been evaluated for each biomass. Fig. 4 compares particle size distributions after grinding of raw and torrefied biomass. Cumulative mass fractions show clearly the relative product grindability: the higher the fines mass fractions, the more grindable the product.

Torrefaction has a great impact on wood chips grindability. Compared to raw materials with only 20 wt.% of particles below 1 mm,

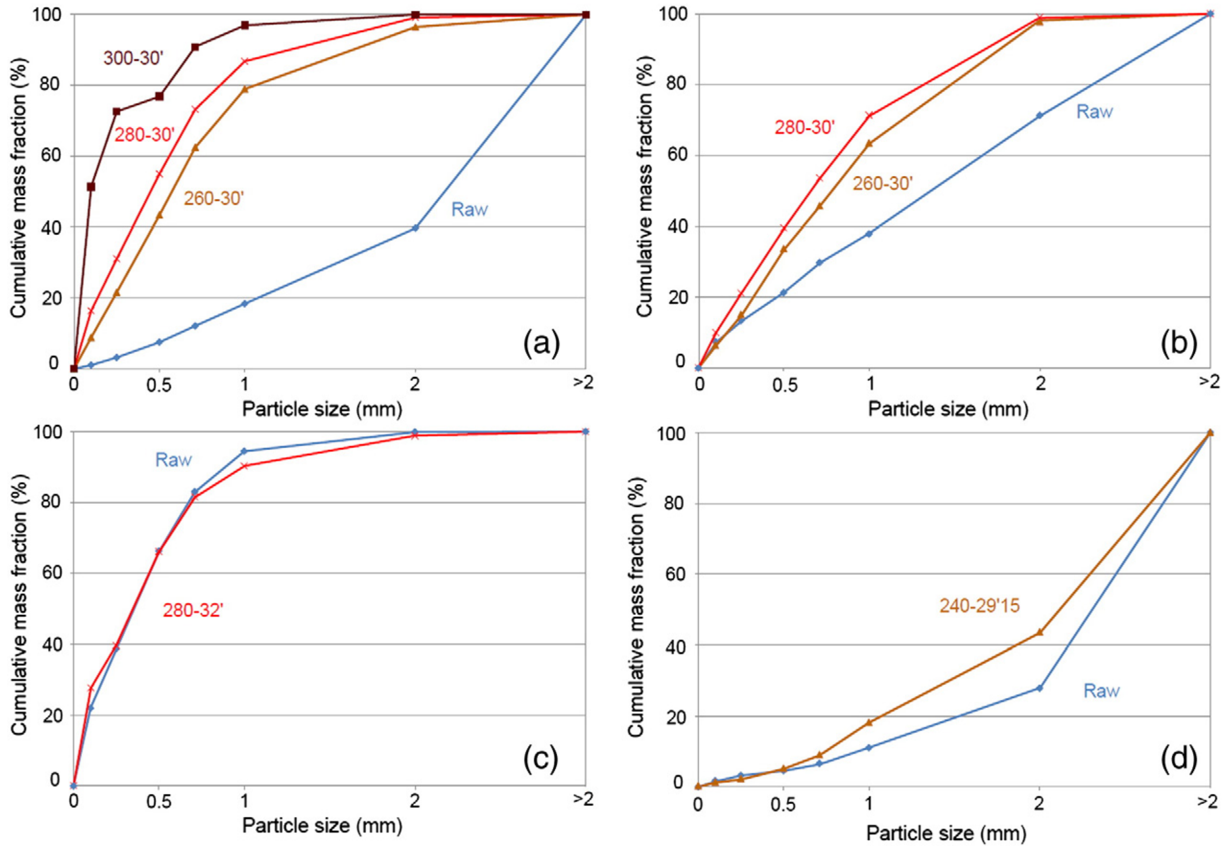

Fig. 4. Particle size distributions after blade grinder of torrefied (a) wood chips, (b) olive pips, (c) pine barks and (d) straw.

after 30 min at every temperature, more than 80 wt.% of particles are below 1 mm. At 300 °C, close to 80 wt.% of particles are even below 0.5 mm and 50 wt.% are below 0.1 mm. This kind of grindability enhancement is needed for applications like gasification or co-firing [1]. Nevertheless, the grindability reached at 300 °C is too high for pellet production, due to a high loss of biomass mechanical properties [7]. Torrefied wood chips obtained at 260 °C, or even 280 °C, should be more suitable for pelletization. Olive pip grindability was also improved after torrefaction, contrary to pine bark and straw which remain respectively easily and poorly grindable.

3.5. Mass and energy yields

Advanced studies on wood chip torrefaction were made in order to determine mass and energy balances with specific runs. Solid mass yields (Y_S) are calculated on as received basis (mass of solid (m_S) over mass of wet biomass (m_B)) which is the best way from an industrial point of view:

$$Y_S = m_S/m_B$$

From HHV calculation, energy yields (η_S) can also be estimated. HHV are calculated on a dry basis, this is the reason why energy yields are calculated from dry basis mass yields, without initial moisture (θ_B). It should be noted that energy yields could be also calculated, with exactly the same result, from as received mass yields but with HHV recalculated with respect to biomass moisture. Energy densification (d_η) is then calculated on an as received basis.

$$\eta_S = \frac{Y_S}{1-\theta_B/100} \cdot \frac{\mathrm{HHV}_S}{\mathrm{HHV}_B} \quad \text{and } d_\eta = \eta_S/Y_S$$

Table 5 lists specific runs made with wood chips and gives mass yields, energy yields and energy densifications as results.

Mass yields range from 50.8 wt.% at 300 °C to 74.2 wt.% at 260 °C whereas energy yields range from 68.6% to 89.4%. These results are typical, according to literature [32], and correspond to different cases for further applications. Results from 30 min at 260 °C, with almost 90% of the initial biomass energy and a densification of 1.20, are excellent for pellet production where the aim is energy densification with minimal losses. On the other hand, torrefaction at 300 °C for 30 min shows a too low an energy yield for pellet production, even if the energy densification is higher. However, these are good results for co-firing or gasification applications in terms of HHV and grindability.

3.6. Techno-economic discussion

This study on the pilot unit with product analysis and mass balances validates the feasibility of biomass torrefaction in the REVE. As explained in the introduction, this technology is a very interesting potential solution. However, from an industrial development point of view, some techno-economic aspects need to be considered.

First of all, the input material flexibility is shown with four kinds of biomass torrefied in the same pilot unit. Straw is, however, not really feasible because of its low density which entails low mass flow rates. In order to increase mass flow rate, straw pelletization before torrefaction could be a solution, with the aim of making straw pellets hydrophobic [29].

Established according to the grindability [18], the economic target conditions of 250–300 °C for 5–30 min could be extended to all others properties/applications. Residence times have a direct influence on the size of a continuous reactor and for a machine like the REVE, a 15 to 30 min residence time with a tube temperature of 280–300 °C is easily attainable. However, from an economic point of view and for a given mass flow rate, the smaller the machine, the better. As it can be seen on the Fig. 3(a), composition of torrefied wood chips after 15 min at 280 °C is almost the same as torrefied wood chips after 30 min at 260 °C. Therefore, for a similar final result, by increasing temperature from 260 °C to 280 °C, the reactor size could be divided by two. Similar observations can be made between 280 °C and 300 °C.

Table 5
Mass yields (ar), HHV, energy yield and energy densifications of torrefied wood chips at 85 kg/h.

T (°C)	t (min)	Y_S (wt.%)	HHV (MJ/kg)	η_S (%)	d_η
260	30	74.2	20.31	89.4	1.20
280	30	64.3	21.07	80.4	1.25
300	15	59.4	22.06	77.7	1.31
300	30	50.8	22.78	68.6	1.35

Based on these remarks, preliminary additional studies are conducted on the same pilot unit with wood chips (Table 2). Table 6 gives results from ultimate analysis of torrefied wood chips in continuous runs.

At 40 kg/h for 10 min, corresponding to a filling ratio of 13%, a tube temperature of 300 °C is needed to produce torrefied wood chips with an HHV higher than 20 MJ/kg. These kinds of torrefied wood chips are suitable for pellet production. By increasing mass flow rate to 80 kg/h, products obtained at 300 °C are similar to products obtained at 280 °C and 40 kg/h. At 310 °C, there is a low increase of torrefied wood chips HHV, compared to the run at 300 °C. However, it is not sufficient. The difference of results between 40 and 80 kg/h can be explained by the combination of two phenomena: twice the mass to be heated and the bed depth (for cross section) affecting heat transfer. However, with bed depth between 10% and 30%, given the vibro-fluidized characteristics of the device, the mass of product to be heated is the limiting factor. This short additional study shows the importance of parameters such as mass flow rate and bed depth, especially from an industrial development point of view. Nevertheless, it validates the utilization of this pilot unit for continuous biomass torrefaction at 300 °C and 40 kg/h. Higher temperatures have to be studied in future works to obtain biochar continuously.

Once the feasibility of biomass torrefaction into the REVE is proven, a comparison with others torrefaction technologies could be required. Besides the flexibility in using different input materials, others technical points have to be discussed for this comparison. Table 7 summarizes the results of Ref. [26] for six technologies over six criteria: heating medium, quality of particle mixing, quality of heat exchange, product uniformity, scalability and flexibility in using different input materials. An additional row for the REVE completes this table.

Most of the technologies use gas as the heat carrying medium, except the screw type reactors which use hot oil. The REVE uses electricity as its heating medium and this is one of the main differences with others technologies. The quality of particle mixing and heat exchange is acceptable for other technologies except for the moving bed reactor. Due to the direct contact with the confined tube, the heating efficiency of the REVE is excellent, with between 10% and 15% losses. Particle mixing is ensured by the vibrations which can be adapted to the product and the application. Product uniformity, process scalability and flexibility are the main issues of current technologies. Due to its plug flow

Table 6
Ultimate analysis (wt.% on dry basis), and HHV (on dry basis) of torrefied wood chips in continuous runs.

T (°C)	t (min)	Q (kg/h)	A_F (%)	C	H	N	Ash [a]	O [b]	HHV [c]
280	10	40	13	49.53	5.75	0.11	1.0	43.6	19.53
300	10	40	13	52.32	5.46	0.13	1.4	40.7	20.46
300	10	80	26	49.88	5.69	0.12	1.0	43.3	19.62
310	10	80	26	50.53	5.62	0.12	1.0	42.7	19.82

[a] Average value from Ref. [27] and concentrated for dark solids.
[b] Calculated by difference.
[c] Higher heating value in MJ/kg according to Ref. [14].

Table 7
Technologies comparison based on Ref. [26].

Technology	Heating medium	Mixing	Heat exchange	Uniformity	Scalability	Input flexibility
Rotating drum	Gas	+	+	+/−	−	+
Screw type	Hot oil	−	++	+/−	−	−
Multiple furnace	Gas	+	+	+/−	+	+
Torbed reactor	Gas	+	++	+/−	−	− −
Moving bed	Gas	− −	−	−	−	−
Belt dryer	Gas	++	++	+	−	+
REVE	Electricity	++	++	+	+	+

behavior [30] and its current industrial food applications (up to 5 ton/h roasting units), uniformity and scalability are challenges already met by the REVE. Finally, the flexibility in using different input materials is demonstrated in this paper.

Other important criteria for industrial development are energy efficiency and consumption. Comparison of energy consumption between the different technologies is not easy, given the lack of data. However, whatever the technology employed, the theoretical energy required for torrefaction, E_T, will be the same and can be estimated.

$$E_T = E_{h,W} + L_{v,W} + E_{h,B} + \Delta_r H \quad \text{with} \quad \begin{array}{r l} E_{h,W}: & \text{heating of moisture (liquid then vapor)} \\ L_{v,W}: & \text{water heat of vaporization} \\ E_{h,B}: & \text{heating of dry biomass} \\ \Delta_r H: & \text{torrefaction heat of reaction} \end{array}$$

For low degrees of torrefaction, the reaction is considered endothermic and an average value of 100 kJ/kg can be taken [15,33]. Heat capacity of dry wood can be estimated according its temperature [34]. For a biomass with an initial moisture of 10% to 15%, reaching a final temperature between 230 and 250 °C, the energy requirement ranges 690 to 850 kJ/kg. The average value of 770 kJ/kg, or 215 kW h/ton, agrees with results from literature [15]. Typically, for these kinds of operating conditions, the design of a REVE allows a high energy efficiency of around 80–90% which means that the treatment of 1 ton of wood chips would require around 250 kW h.

This power consumption corresponds to around 5% of the dry initial biomass HHV and can be mainly attributed to the drying step. This is the reason why particular attention should be paid to the drying step, currently carried out inside the REVE. Gases and volatiles from torrefaction contain near 10% of dry initial biomass HHV [1]. Technologies using gas as the heat carrying medium need an amount of energy to heat this medium [15] and can use the energy recovered for gases and volatiles combustion in order to be athermal. However, torrefaction gases contain high amounts of water and CO_2 and they are diluted into the carrier gas. This is the reason why additional fuel is often required: natural gas or solids (raw or torrefied biomass) [26].

As gases and volatiles are not diluted with the REVE, this combustion could be even easier. On the other hand, electricity is the energy source for the REVE and the heat recovered from combustion cannot be used directly. Energy optimization could be carried out with a pre-heating step, or even pre-drying step, using this heat. This heat integration, in order to reduce the power consumption, will be studied in future works and should be integrated into the overall efficiency of a complete torrefaction/power plant.

4. Conclusions

Using the same pilot unit, four kinds of biomass have been torrefied, validating the use of REVE technology for this application and its flexibility using different input materials. Solids have been analyzed, showing the impact of torrefaction in elemental composition (and HHV) and grindability. With a residence time up to 30 min, torrefied wood chips mass yields range from 50.8 wt.% at 300 °C to 74.2 wt.% at 260 °C and energy yields range from 68.6% to 89.4%. Finally, a preliminary continuous study was successfully conducted at 300 °C, validating the utilization of this pilot unit as a demonstration plant at 40 kg/h.

Compared to other technologies, REVE meets all technical challenges such as particle mixing, heat exchange, product uniformity, scalability and flexibility with input materials. However, currently, torrefaction gases are not recovered and heat integration has to be considered further. This is why additional studies must be conducted: torrefaction of straw pellets, recovery and use of heat from gas combustion and heat integration of an industrial unit.

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